Senior Thesis

Ascent Rates of the Egersund Dikes

by
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Approved by :

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ABSTRACT

Continental flood basalts are well studied examples of geologics processes that produce enormous amounts of rock inonly a short time. However, the feeder dikes for these CFB's are less well studied in that their ascent rates and flow are unknown. The Egersund dikes of SW Norway are possible CFB feeder dikes associated with the opening of the Iapetus Ocean. For this paper, a program utilizing physical properties and magma composition has calculated ascent rates and volumetric flow for two samples of the Egersund dikes. The data produced by the program indicates ascent rates up to 9 m/sec and volumetric flow of over a km^3 per day. The ascent rates are controlled by viscosity, higher values giving slower flow and vice versa. The viscosity in turn is controlled by magma composition or more specifically the amount of SiO_2 and Al_2O_3. Higher amounts of the framework oxides increase the viscosity and decrease flow velocity. Water content decreases viscosity and incerases flow velocity. Most of the data produced is useless, however, because turbulent flow of the magma makes calculations used unreliable. Further study using calculations compatible with turbulent is needed.

INTRODUCTION

The popular view of geology is that of colossal forces shaping the earth over hundreds of millions of years. In reality, many geological processes speed to completion during intervals of days or even hours. The flow of magma in continental flood basalts (CFB's) is one of these rapid processes. Studies estimate the eruption of $700km^3$ of the Columbia River basalts in only a few days with average extrusion rates of 10^{-1}-$10^{-2}km^3$ per day along each km of active fissures (Barton and Miller, 1991). The emplacement of dikes that fed the CFB's are less well known. For such rapid magma flow at low surface temperatures and pressures after extrusion, the flood basalts would require feeder dikes under high pressure with magma traveling at rates comparable to if not faster than the extrusion velocities. However, few studies that calculate ascent rates and volumetric flow for CFB magma exist.

The calculation of ascent rates requires determining the physical properties, density and viscosity, of magma. Data on physical properties combined with the dike geometry and entered into flow calculations will yield flow velocities. The physical properties, density and viscosity, control how the magma responds to outside stresses acting upon it such as the stresses that drive the flow of dikes. Magma density controls buoyancy and the ascent of magma through the lithosphere. Because density is mostly a function of the composition, the rise of magma through the low density lithosphere may only be possible for a limited range of compositions. Viscosity is the resistance of the magma or any other fluid to flow. Fluids flow or deform in response to a shear stress acting on the fluid. The rate of this deformation is viscosity and a high viscosity means a liquid deforms slowly when under high shear stress; it flows at low velocity. Honey or tar are high viscosity liquids. Viscosity is dependent on chemical composition because the resistance to flow represents the degree of polymerization in a magma. Polymerized magmas, those with high SiO_2% and Al_2O_3%, high viscosity. The temperature at which a magma crystallizes also varies the viscosity. Consequently siliceous, low temperature magmas (rhyolites) have a high viscosity and flow slowly while mafic, high temperature magmas (basalts) have low viscosity and flow at higher velocities. The differences in eruptive styles between basalts and more evolved magmas are a direct result of the viscosity differences. Additionally, higher pressure affects viscosity by allowing more dissolved water into the magma which decreases viscosity. The water serves to decrease polymerization by hydrolizing bridging oxygens in the Si-Al-O framework. It follows then that the determination of flow velocity in a CFB dike requires knowledge of the chemical components of the magma, its pressure, and its temperature.

The task of this paper is to calculate the ascent rates, volumetric flow, velocitiy profile, and the dependence of these facts on composition for dike samples related to CFB activity. Unfortunately, most post-Precambrian CFB provinces are severely altered making accurate chemical study difficult. The Egersund Dikes of SW Norway, however, may be the solution to the problem of fresh samples. The dikes, varying in width from 0.3m to 30m, were emplaced in a swarm, cutting Precambrian country rock along N70 W trending faults. Isotope dating puts the age at 630-650 m.y. All of the field data is consistent with the time of the opening of the Iapetus Ocean. Rifting associated with the opening may have led to CFB activity fed by the Egersund Dikes. Any basalt flows supplied by the dikes are absent due to erosion that has removed 3km from the original land surface. Whether the dikes are actually associated with pre-Iapetus rifting is uncertain because rotation of Norway during the Proterozoic obscures the original orientation of the rifting. The dikes consist of Olivine-tholeiites, tholeiites, and hawaiites. Many olivine phenocryts and glass margins are present which attests to the freshness of the samples (Barton and Miller, 1991). This study uses the compositions of two samples from the Egersund Dikes for the calculation of flow velocities ,and hence, the ascent rate. The samples represent approximate compositonal end members of the dikes: **sample 1)** a mafic rock with phenocrysts of olivine, pyroxenes, and plagioclase, probably an Olivine-tholeiite, **sample 2)** a more evolved thoeiitic basalt with large amounts of plagioclase phenocrysts. A clearer picture of how the flow velocity varies with composition should be possible with the diverse compositions. In addition to flow velocity, the calculations will yield maximum flow velocity, volumetric flow and a profile of velocity across the width of the dike.

METHODS

The methods of this study start with the determination of composition and the temperature of the magma. Pressure has already been calculated to be 5 kilobars (Barton and Miller, 1991). The the data is used in density and viscosity calculations whose results are then entered into flow velocity equations which will provide the final results: flow velocity, maximum flow, volumetric flow, and a velocity profile.

The first step, microprobe analysis, will provide compositional data. Dr. Michael Barton will also use the data to calculate magma temperature, required for the viscosity calculations, with a plagioclase thermometer.

The flow calculations come next and will use the equations below. The equations are given for descriptive purposes. The actual manipulation of the equations of density and viscosity and their application to flow velocity calculations are done and reported by a flow velocity analysis program written by Dr.Barton (appendix B).

Calculating Magma Density

The technique for density calculation uses partial molar volumes of the component oxides (Appendix A1) and calculations determined by Bottinga and others (1982). The partial molar volume of a component **i** (V_i) is the change in volume caused by a change in the number of moles of the component (n_i) at constant pressure, temperature, and molar amount of the other components.

$$V_i = (\partial V / \partial n_i) \qquad (1\text{-}1)$$

The volume (**V**) of a magma of many components is expressed by

$$V = V_a n_a + V_b n_b + \ldots + V_i n_i = \sum V_i n_i \qquad (1\text{-}2)$$

The equation can be simplified by expressing the components as mole fractions (X_i) or simply dividing each side of equation 1-2 by the total number of moles of all the components ($n_a + n_b + \ldots + n_i$). The division yields an equation of molar volume (V_m).

$$V_m = \sum V_i X_i \qquad (1\text{-}3)$$

The density of the magma (p) is then calculated by dividing the molar volume into the molecular weight of the magma.

$$p = \sum M_i X_i \,/\, \sum V_i X_i \qquad (1\text{-}4)$$

The term $\mathbf{M_i}$ is the molecular weight of a component **i**.

Calculating Magma Viscosity

The method used for calculating magam viscosity is similar to that of density in that the components of magma are included, but magma temperature is also needed. When calculated, viscosity is expressed in Pascals (Pa) or Newtons per meters squared per second ($Nm^{-2}s^{-1}$). The calculations, devised by Shaw (1972), are particularly useful because the effect of water content is taken into effect. The calculations start with an acknowledgement that viscosity (μ) is temperature dependent by the Arrhenius relation

$$\mu = \mu_o e^{E/RT} \tag{1-5}$$

where μ_o is constant, **E** is the activation energy, **R** is of course a constant, and **T** is in K. The equation is put into logarithmic form

$$\ln\mu = \ln\mu_o + (E/R)1/T \tag{1-6}$$

Plots of $\ln\mu$ versus **1/T** for simple silicate mixtures converge on the value of viscosity and show variations in slope that depend on the composition. With this relationship the magma viscosity is calculated by

$$\ln\mu = S(10^4/T) - C_T S + C_\mu \tag{1-7}$$

where **S** is the slope dependent on the composition. The constant values $C_T S$ and C_μ are points of intersection on the plot: $C_T S = -6.4$ and C_μ

= 1.5. **S** is calculated using the mean partial molar activities for each component or **E**, determined by Shaw (1972) and shown in Appendix A2. The summation of these values are multiplied by the mole fraction of SiO2 and the component **i**, then divided by one minus the mole fraction of SiO2 to get the mean slope (**S**)

$$S = \sum X_i X_{SiO_2} / 1 - X_{SiO_2} \tag{1-9}$$

Calculating Magma Flow Velocity

The method uses calculations that incorporate dike geometry, density and viscosity, and assumptions about the character of the magma (Philpotts, 1990).

The assumptions will be discussed first because they are most important to the validity of the flow calculations. The first given is that of fluid type. The magma ust be considered a Newtonian fluid, a designation relating to viscosity. Remembering that viscosity is a ratio of shear stress to shear strain, a Newtonian fluid exhibits a linear relationship between the two. As stress increases, the strain increases. Most magmas are Newtonian but some that have suspended crystals or gases respond to stress much differently and are inappropriate for this study. The magma responsible for the intrusion of the Egersund Dikes was Newtonian. The Newtonian character is a requirement for the second assumption, laminar flow (figure 1). A shear stress is applied a liquid between to parallel plates. Fluid in contact with the upper plate moves at a velocity *v* while liquid touching the lower plate is still. Fluid inbetween moves as a series of parallel plates or lamellae sliding over the plate beneath it. This condition is laminar flow as opposed to the other conditon, turbulent flow. In turbulent conditions, flow velocity fluctuates constantly making any quantitative analysis of the flow beyond the scope of this study. Data entered into the flow velocity program used for this study may result in turbulent flow and therefore renders any results untrustworthy. Characterizing the flow is accomplished in the program by a Reynolds number (Re) equation

$$\mathbf{Re} = \mathbf{2r}\rho\mathbf{v_a} \;/\; \mu \qquad (1\text{-}10)$$

where $\mathbf{r}$ is the radius of the dike and v_a is the average velocity across the dike, a product of the flow velocity calculations that are to follow. A Reynolds number of under 2300 indicates laminar while anything larger is turbulent flow.

Given the underlying assumptions of flow character , the flow velocity calculations using dike geometry and physical properties of the magma are now possible. The calculations begin by considering a small volume of magma acted on by external forces in figure 2 (Barton, 1990). Because flow is assumed to be laminar with constant velocity, the sum of the forces is zero

$$-\mathbf{dxdydz}\rho\mathbf{g} - \mathbf{dPdxdy} + \mathbf{d}t\mathbf{dydz} = \mathbf{0} \qquad (1\text{-}11)$$

Dividing by **dzdy** and solving for **d*t*** gives

$$\mathbf{d}t = (\rho\mathbf{g} - \mathbf{dP/dz})\mathbf{dx} \qquad (1\text{-}12)$$

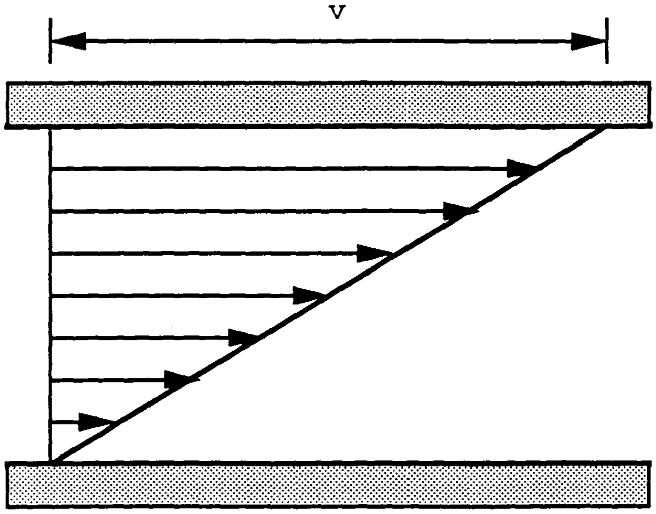

Figure 1 Laminar flow of liquid between parallel plates, v is velocity relative to lower plate (Philpotts, 1990)

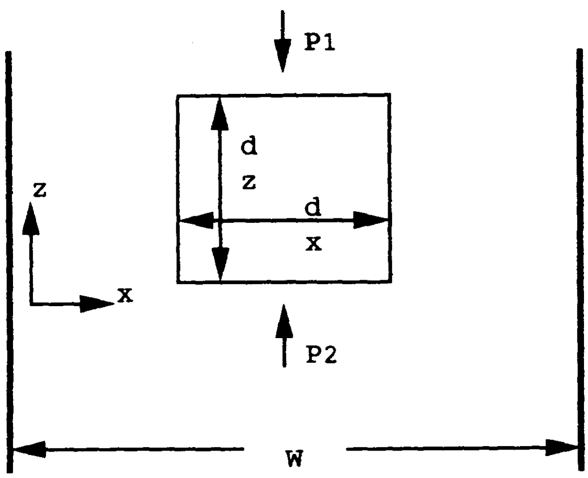

Figure 2 Small volume of magma used for flow velocity calculations and representation of acting forces (Barton, Geol. Sci. 629 class notes, 1991)

Gravitational fprce = v*p* g = dxdydz*p* g

Force due to pressure gradient = dPdxdy

Shear force = dt dydz

Integrating equation 1-12 yields the value of **t** for any point **x** across the dike.

$$t = (\rho g + dP/dz)x + constant \quad (1\text{-}13)$$

In the middle of the dike (**x = W/2**) the shear stress is zero and the constant can then be evaluated

$$constant = -(\rho g + dP/dz)W/2 \quad (1\text{-}14)$$

Combining 1-13 and 1-14 gives

$$t + (\rho g + dP/dz)(x - W/z) \quad (1\text{-}15)$$

The definition of viscosity, shear stress divided by strain, allows the use of equation 1-15 for velocity.

$$\mu = t/strain \quad (1\text{-}16)$$

Strain in this case is velocity at a point **x** in the dike.

$$\mu = t/(dv/dx) \quad (1\text{-}17)$$

Equation 1-17 is solved for **t** and the result is entered in equation 1-15 giving

$$\mu(dv/dx) = (\rho g + dP/dz)(x - W/2) \quad (1\text{-}16)$$

$$dv = 1/\mu(\rho g + dP/dz)(x - W/2)dx \quad (1\text{-}17)$$

Equation 1-17 is integrated.

$$v = 1/\mu(\rho g + dP/dz)(x^2 - Wx) + \text{constant} \qquad (1\text{-}18)$$

When x is zero, v is then zero and the constant is zero. Equation 1-18 can be simplified further to

$$v = -1/2\mu(\rho g + dP/dz)(Wx - x^2) \qquad (1\text{-}19)$$

Average velocity (v_a) is calculated by integrating the velocity over the width of the dike and dividing by the width

$$v_a = 1/W \int -1/2\mu(\rho g + dP/dz)(Wx - x^2)dx \qquad (1\text{-}20)$$

Evaluating the integral gives

$$v_a = -1/12\mu(\rho g + dP/dz)W^2 \qquad (1\text{-}21)$$

The maximum velocity comes from taking the first derivative of equation 1-19

$$dv/dx = -1/2\mu(\rho g + dP/dz)(W - 2x) \qquad (1\text{-}22)$$

and solving for x giving

$$x = W/2 \qquad (1\text{-}23)$$

which is the center of the dike. Theoretically, the velocity profile across the rest of the dike decreases from the center to the margins. The effects of friction and cooling on the magma at the margins is probably the cause of the velocity decrease.

The equation for volumetric flow (**Q**), given by Shaw (1965), is

$$\mathbf{Q = P(s1s2)2ç / 4\mu l} \qquad (1\text{-}24)$$

where **s1** and **s2** are the dimensions of a rectangular cross section of the dike, **ç** = 0.32**s1/s2** as long as **s1/s2** < 0.1, and **l** is the length of the cross section.

The composition, temperature, and pressure of two Egersund Dike samples are entered into the flow velocity analysis program. Sample 1 represents the mafic end of composition possible in the dikes. Sample 2 has a more evolved,slightly less mafic composition higher in SiO_2 and Al_2O_3.

For samples 1 and 2, the compositonal data from table I are the input for the program. Dr. Barton reports water content for sample 1, determined by glass analyses, to be essentially zero and that of sample 2 as 1.02%. The water content is varied as an input to illustrate its effect on the results. In addition, from thermometer calculations, a temperature of 1400 K for sample 1 and temperature a 1475 K for sample 2 along with the pressure of 5 kilobars are also inputs. The final inputs are
possible widths of the dike in meters and the length, arbitrarily set at 1000 meters. The length has little bearing on the calculations other than contributing significant digits. A crustal density of 2900 kg/m^3 is assumed. Using the data, the program calculates the average velocity, maximum velocity, volumetric flow rate, and the velocity profile.

RESULTS AND DISCUSSION

The output of the flow velocity program is in table II for sample 1 and table III for sample 2. Among the data are patterns that illustrate the controls of magma flow. Of course, the data also gives numbers on the flow velocity, volumetric flow, and flow profile.

The first notable pattern is the small dike widths used for both samples. Other widths were tried in the program but all the results had turbulent flow. Even the data reported in tables II and III includes mostly examples of turbulent flow. The reason for the limited dike geometry can be attributed to the Reynolds number equation (1-10). In the equation the width and Reynolds number are directly proportional. Consequently higher widths give larger Reynolds numbers and turbulent flow. Obviously, the program in use for this study works well only for thin Egersund dikes of one or two meters.

The second pattern, though not surprising, is important because it confirms the role of H_2O and pressure in viscosity. Figure 3 shows the H_2O - viscosity relationship inversely proportional, in fact from the graph the relationship appears logarythmic. By exstension, higher pressures that allow higher water content could decrease viscosity.

A third fact is viscosity's effect on flow character and velocity. Tables II and III show turbulent flow for most of the lower viscosity cases. As with dike width, the bias towards turbulence comes from the Reynolds number equation (1-10). Viscosity has an inverse relationship with the Reynolds number; a low viscosity leads to a high Reynolds number and possibly turbulent flow. Viscosity as it relates to ascent rates can be seen in table III. At 0.00% water and a vicosity of 19.43 Pa, the average flow velocity is 3.67 m/sec, a fairly quick pace.

Oxide	Sample 1	Sample 2
SiO_2	48.72	49.09
TiO_2	1.82	2.08
Al_2O_3	16.94	17.03
FeO	11.69	9.28
MgO	7.55	7.80
CaO	10.25	10.47
Na_2O	2.45	2.70
K_2O	0.57	0.52
H_2O	0.00	1.04
Total	99.56	97.83

Table I Composition of Egersund Dike samples

dike width (meters)	water content (wt. %)	viscosity (pascals)	ave. velocity (m/sec)	max. velocity (m/sec)	volumetric flow (cubic m/sec)
2	0.00	18.65	7.94	11.91	15880.29
	0.52	14.53	15.56*	23.34*	31120.17*
	1.05	9.23	27.9*	41.85*	55805.06*
	2.00	6.82	75.00*	112.51*	150013.1*
3	0.00	18.65	26.8*	53.6*	14684.4
	0.52	14.53	48.56*	76.86*	28776.61*
	1.05	9.23	94.17*	188.34*	51601.6*
	2.00	6.82	151.4*	253.12*	13871.6*

Table II Flow data for Sample 1, * denotes turbulent flow, results should be ignored

dike width (meters)	water content (wt. %)	viscosity (pascals)	ave. velocity (m/sec)	max. velocity (m/sec)	volumetric flow (cubic m/sec)
1	0.00	19.43	3.67	5.5	3665.16
	0.52	13.50	9.29	13.94	9291.87
	1.05	11.83	13.25*	19.87*	13249.29*
	2.00	8.43	17.23*	27.81*	18931.34*
2	0.00	19.43	14.66*	21.99*	29321.24*
	0.52	13.50	23.73*	34.84*	59742.33*
	1.05	11.83	33.27*	49.9*	66539.4*
	2.00	8.43	56.34*	75.81*	45783.93*

Table III Flow data for Sample 1, * denotes turbulent flow, results should be ignore

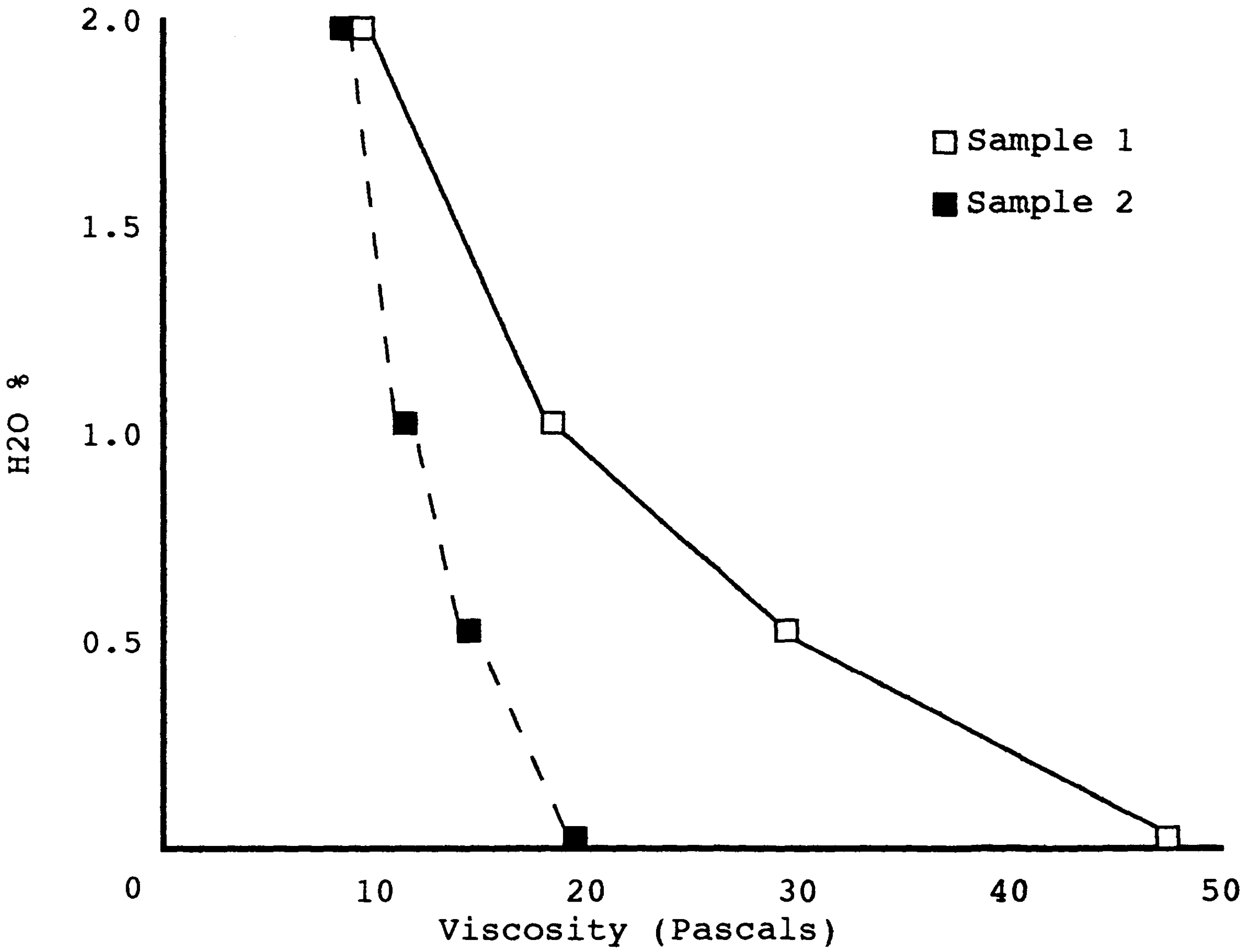

Figure 3 Relationship of water content to viscosity

But the change in viscosity, with 0.5% water, to 13.50, increases average flow velocity to 9.29 m/sec, nearly the pace of an Olympic 100m dash.

Data on the velocity profile in the dike is consistent for all the samples. Figure 4, the profile for Sample 2 at 0.00% water, is representative. The numbers confirm that magma experiences maximum velocity in the center of the dike and decreasing velocities towards the margins, similar to the graphical interpretation in figure 5 .

The effect of compositon on flow velocity appears in the data. The results indicate that composition directly effects flow. Sample 1, the mafic example, predictably has a lower viscosities than comprable situations with the same water content in sample 2. This fact agrees with the expectation that compositions with less SiO_2 and Al_2O_3 are less viscous. As a consequence, the less viscous compositions should have higher velocities because of the viscosity - velocity relationship and the data in tables II and III agree. The cases where the sample has 0.00% water in samples 1 and 2 have average velocities of 7.94 m/sec and 3.67 m/sec, respectively. Therefore, as magma composition becomes more derived, the potential velocity of the magma under uniform conditions will decrease.

Finally, the ascent rates and volumetric flow rates themselves are part of the data as flow velocities. The mafic Sample 1, with an ascent rate of 7.94 at 0.00% water, would traverse thick continental crust of say 140km in a little over five hours.
The slower, derived magma, Sample 2, would travel the same distance in 7.5 hours or possible four hours depending the water content. The resulting volumetric flow per second would be massive (tables II,III). Daily rates would be 5.7 * $10^6 km^3$ for sample 1 and sample would have rates of 1.3 * $10^6 km^3$ to 3.3 * $10^6 km^3$ depending on water content. The

discrepancy in volumetric flow for samples 1 and 2 a similar velocities is due to the different dike widths.

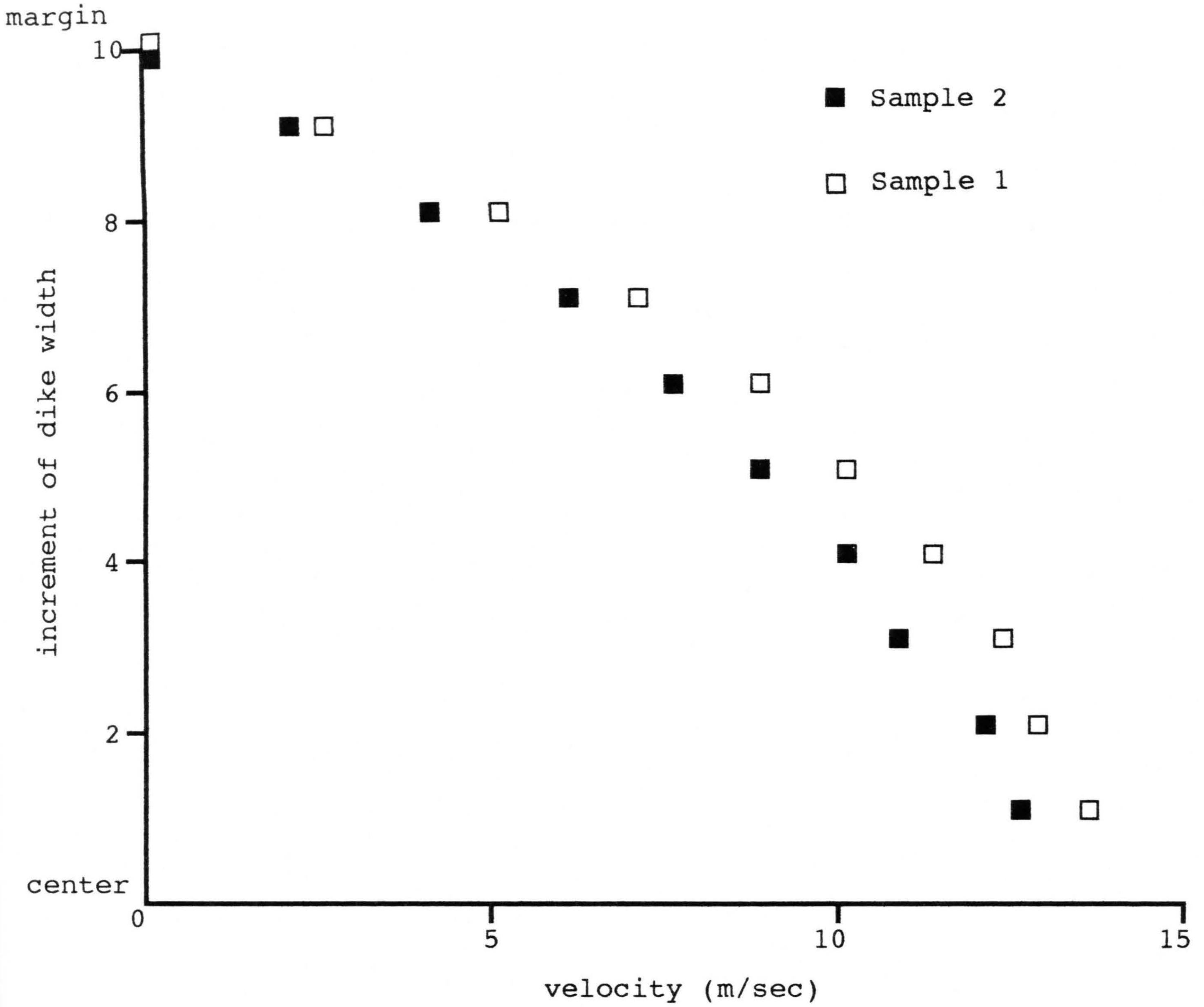

Figure 4 velocity distribution within dike

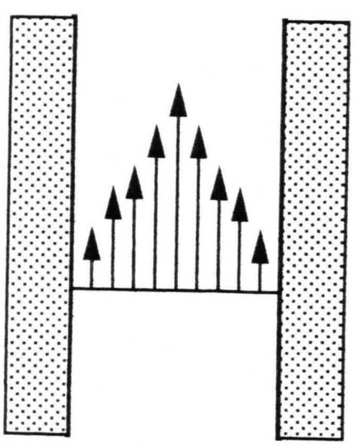

Figure 5 Graphic of theoretical velocity profile of a dike (Philpotts, 1990)

CONCLUSIONS

Upon investigating the ascent rates of the Egersund dikes several conclusions are possible. The ascent rates themselves are impressive and make traversing of the crust a matter of hours for even the slowest dike. The resulting volumetric flow is equally impressive with daily rates exceeding a cubic kilometer of magma. The ascent rates depend on certain characters of the magma. The physical property of viscosity is a key controller of the magnitude of the ascent rate. Composition effects ascent rates by controlling viscosity. Increasing amounts of framework oxides, SiO_2 and Al_2O_3, slow the ascent rates with increasing viscosities. Water content serves to decrease the viscosity and increase ascent rate. Within the dike velocity changes depending on the position relative to the center of the dike. The highest velocities are at the center and decrease towards the margins. The data for this study is extremely limited because of the difficulty in calculating velocities for turbulent flow, which appears to dominate flow character in the samples used. Therefore, study involving the use of turbulent flow calculations, is the next logical step.

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Appendix Section

Oxide	Molar Volume
SiO_2	26.75
TiO_2	22.45
Al_2O_3	37.80
FeO	44.40
MgO	13.94
CaO	12.32
Na_2O	16.59
K_2O	46.30

Appendix A1 Partial molar volumes of common oxides of silicate liquids of 40 to 80 mol % SiO_2 at 1400 C (Bottinga and Weill, 1970 and Bottinga et al., 1982)

Oxide	Partial molar activation energies
H_2O	2.0
K_2O, Na_2O, Li_2O	2.8
MgO, FeO	3.4
CaO, TiO_2	4.5
AlO_2	6.7

Appendix A2 Partial molar activation energies of common oxides (Shaw, 1972)

```
10 PRINT "*************************************************"
20 PRINT "VISCDEN: A PROGRAM TO CALCULATE DENSITIES, VISCOSITIES, "
30 PRINT "AND LAMINAR FLOW RATES OF MAGMAS. DENSITIES CALCULATED "
40 PRINT "FOLLOWING LANGE AND CARMICHAEL (1990, REVIEWS IN "
50 PRINT "MINERALOGY, VOL 24) AND KRESS AND CARMICHAEL (1991, CMP, "
60 PRINT "108, 82-92). VISCOSITIES CALCULATED FOLLOWING SHAW (1972,"
70 PRINT "AM. J. SCI., 272, 870). THE EFFECTS OF PRESSURE ON "
80 PRINT "DENSITY AND VISCOSITY ARE TAKEN INTO ACCOUNT. THE PRESSURE"
90 PRINT "CORRECTION TO VISCOSITY IS APPROXIMATE. THE EFFECTS OF "
100 PRINT "H2O ON MAGMA DENSITY ARE ALSO APPROXIMATE. "
110 PRINT "NOTE THAT NON-LAMINAR (TURBULENT) FLOW IS NOT TREATED."
120 PRINT "*************************************************"
130 REM
```

```
150 REM
160 DIM O$(11)
170 DIM O(11),M(10),MP(11),MF(11),XV(11),MX(11),V(10),A(10),V1(11),V2(10)
180 DIM VT(11),VP(11),MS1(11),MS2(5),MS3(5),MS4(5)
190 DIM RO1(10),ROP(10),WD1(10),WDP(10)
200 DIM DP(10),DD(10)
210 REM
220 REM *** READ DATA ***
230 REM
240 RESTORE 280
250 FOR I=1 TO 11
260 READ O$(I)
270 NEXT I
280 DATA SIO2,TIO2,AL2O3,FE2O3,FEO,MGO,CAO,NA2O,K2O,H2O,TOTAL
290 RESTORE 330
300 FOR I=1 TO 10
310 READ M(I)
320 NEXT I
330 DATA 60.0848,79.899,101.961,159.6922,71.846,40.311,56.0974,61.979,94.196,18.
0152
340 REM
350 RESTORE 390
360 FOR I=1 TO 10
370 READ V(I)
380 NEXT I
390 DATA 26.90,23.16,37.11,42.13,13.65,11.45,16.57,28.78,45.84,20
400 RESTORE 440
410 FOR I=1 TO 10
420 READ A(I)
430 NEXT I
440 DATA 0.00,7.24,2.62,9.09,2.92,2.62,2.92,7.41,11.91,0
450 FOR I=1 TO 10
460 A(I)=A(I)*10^-3
470 NEXT I
480 RESTORE 520
490 FOR I=1 TO 11
500 READ V1(I)
510 NEXT I
520 DATA -1.89,-2.31,-2.26,-2.53,-0.45,0.27,0.34,-2.40,-6.75,0,10.18
530 FOR I=1 TO 11
540 V1(I)=V1(I)*10^-4
550 NEXT I
560 RESTORE 600
570 FOR I=1 TO 10
580 READ V2(I)
590 NEXT I
600 DATA 1.3,0,2.7,3.1,-1.8,-1.3,-2.9,-6.6,-14.5,0
610 FOR I=1 TO 10
620 V2(I)=V2(I)*10^-7
630 NEXT I
640 REM
650 RESTORE 690
660 FOR I=1 TO 5
670 READ MS2(I)
680 NEXT I
690 DATA 6.7,3.4,4.5,2.8,2.0
700 RESTORE 740
710 FOR I=1 TO 10
720 READ DP(I)
730 NEXT I
740 DATA 1,2,3,4,5,6,7,8,9,10
750 RESTORE 790
760 FOR I=1 TO 10
770 READ DD(I)
```

```
800 REM
810 REM *** INPUT DATA ***
820 REM
830 PRINT
840 PRINT "ENTER HEADING ";
850 INPUT H$
860 PRINT
870 FOR I=1 TO 10
880 PRINT "ENTER ";O$(I);
890 INPUT O(I)
900 NEXT I
910 PRINT
920 INPUT "ENTER T IN K (SKIP FOR C) ";TK
930 IF TK>0 THEN GOTO 970
940 PRINT
950 INPUT "ENTER T IN C ";TC
960 TK=TC+273
970 PRINT
980 INPUT "ENTER PRESSURE IN BARS (SKIP FOR KB) ";PB
990 IF PB>0 THEN GOTO 1030
1000 PRINT
1010 INPUT "ENTER PRESSURE IN KB ";PKB
1020 PB=PKB*1000
1030 REM
1040 O(11)=0
1050 FOR I=1 TO 10
1060 O(11)=O(11)+O(I)
1070 NEXT I
1080 FOR I=1 TO 10
1090 O(I)=100*(O(I)/O(11))
1100 NEXT I
1110 FOR I=1 TO 10
1120 MP(I)=O(I)/M(I)
1130 NEXT I
1140 MP(11)=0
1150 FOR I=1 TO 10
1160 MP(11)=MP(11)+MP(I)
1170 NEXT I
1180 FOR I=1 TO 10
1190 MF(I)=MP(I)/MP(11)
1200 NEXT I
1210 REM
1220 REM *** CALCULATE DV/DT ***
1230 REM
1240 FOR I=1 TO 10
1250 VT(I)=(A(I)*(TK-1673))*MF(I)
1260 NEXT I
1270 REM
1280 REM *** CALCULATE DV/DP ***
1290 REM
1300 VXS=10.18*10^-4
1310 FOR I=1 TO 9
1320 VP(I)=MF(I)*(V1(I)+V2(I)*(TK-1673))+VXS*MF(3)*MF(
1330 NEXT I
1340 REM
1350 VP(10)=MF(10)*(.1/1000)
1360 FOR I=1 TO 10
1370 XV(I)=(MF(I)*V(I))+VT(I)+(VP(I)*(PB-1))
1380 NEXT I
1390 XV(11)=0
1400 FOR I=1 TO 10
1410 XV(11)=XV(11)+XV(I)
1420 NEXT I
1430 FOR I=1 TO 10
```

```
1460 MX(11)=0
1470 FOR I=1 TO 10
1480 MX(11)=MX(11)+MX(I)
1490 NEXT I
1500 REM
1510 DEN=MX(11)/XV(11)
1520 CLS
1530 PRINT
1540 PRINT "RESULTS FOR ";H$
1550 PRINT
1560 PRINT "WT % H2O          = ";O(10)
1570 PRINT
1580 PRINT "TEMPERATURE, K  = ";TK
1590 PRINT "PRESSURE, BARS  = ";PB
1600 PRINT
1610 PRINT "DENSITY, KG M^3 = ";DEN*1000
1520 REM
1630 REM *** CALCULATE VISCOSITY ***
1540 REM
1650 CT=1.5:CN=-6.4
1660 FOR I=1 TO 10
1670 MS1(I)=MP(I)
1580 NEXT I
1690 MS1(3)=MS1(3)*2:MS1(4)=MS1(4)*2
1700 MS1(11)=0
1710 FOR I=1 TO 10
1720 MS1(11)=MS1(11)+MS1(I)
1730 NEXT I
1740 FOR I=1 TO 10
1750 MS1(I)=MS1(I)/MS1(11)
1760 NEXT I
1770 REM
1780 FOR I=1 TO 5
1790 MS3(I)=MS1(1)*MS2(I)
1800 NEXT I
1810 A=MS1(3)*MS3(1):B=(MS1(4)+MS1(5)+MS1(6))*MS3(2)
1820 C=(MS1(2)+MS1(7))*MS3(3):D=(MS1(8)+MS1(9))*MS3(4)
1830 E=MS1(10)*MS3(5)
1840 SUM=A+B+C+D+E
1850 XS=1-MS1(1)
1860 EMC=SUM/XS
1870 LNMU=EMC*((10^4)/TK)-EMC*CT+CN
1880 MU=EXP(LNMU)
1890 LOGUP=LOG(MU)/LOG(10)
1900 REM
1910 REM *** MU IN POISE ***
1920 REM
1930 MUP=MU*.1
1940 LOGMU=LOG(MUP)/LOG(10)
1950 PRINT
1960 PRINT "LOG VISCOSITY  (1 BAR)  = ";LOGMU
1970 PRINT "VISCOSITY, PA'S (1 BAR) = ";MUP
1980 PRINT
1990 IF PB=1 THEN GOTO 2260
2000 PKB=PB/1000
2010 INPUT "ENTER PRESSURE CORRECTION FOR BASALT (B), ANDESITE (A) OR RHYOLITE (
R) ";PCOR$
2020 IF PCOR$="R" THEN GOTO 2100
2030 IF PCOR$="r" THEN GOTO 2100
2040 IF PCOR$="A" THEN GOTO 2080
2050 IF PCOR$="a" THEN GOTO 2080
2060 LNVP=LOGUP+(-.004300546#*PKB)+(-4.999829*10^-4*PKB^2)
2070 GOTO 2110
2080 LNVP=LOGUP+(-.0548512128#*PKB)+(.0017574514#*PKB^2)
```

```
2110 PRINT
2120 IF PCOR$="B" THEN PCOR$="BASALT"
2130 IF PCOR$="b" THEN PCOR$="BASALT"
2140 IF PCOR$="A" THEN PCOR$="ANDESITE"
2150 IF PCOR$="a" THEN PCOR$="ANDESITE"
2160 IF PCOR$="R" THEN PCOR$="RHYOLITE"
2170 IF PCOR$="r" THEN PCOR$="RHYOLITE"
2180 TURD=LNVP*LOG(10)
2190 MUPR=EXP(TURD)
2200 MUPR=.1*MUPR
2210 LOGVPR=LOG(MUPR)/LOG(10)
2220 PRINT "PRESSURE CORRECTION USES DATA FOR ";PCOR$
2230 PRINT "NOTE: THIS CORRECTION IS APPROXIMATE "
2240 PRINT "LOG VISCOSITY  (P)    = ";LOGVPR
2250 PRINT "VISCOSITY PA S (P)    = ";MUPR
2260 INPUT "ENTER P FOR A PRINTOUT ";PR$
2270 IF PR$="P" THEN GOTO 2290 ELSE GOTO 2330
2280 IF PR$="p" THEN GOTO 2290 ELSE GOTO 2330
2290 INPUT "ENTER G IF PRINTER ON ";PRO$
2300 IF PRO$="G" THEN GOTO 2320 ELSE GOTO 2260
2310 IF PRO$="g" THEN GOTO 2320 ELSE GOTO 2260
2320 GOSUB 4650
2330 PRINT
2340 INPUT "CALCULATE FLOW RATES IN DIKE OR PIPE (Y/N) ";FL$
2350 IF FL$="N" THEN GOTO 3530
2360 IF FL$="n" THEN GOTO 3530
2370 REM
2380 REM *** FLOW IN PIPE ***
2390 REM
2400 INPUT "RADIUS OF PIPE (METERS) ";RD
2410 INPUT "WIDTH OF DIKE (METERS) ";WD
2420 INPUT "LENGTH OF DIKE (METERS) ";LD
2430 INPUT "DENSITY OF CRUST (KG M^3) ";DENC
2440 DELDEN=DENC-(DEN*1000)
2450 PI=3.14159265359#:GA=9.8
2460 DF=DELDEN*GA
2470 INC=RD/10
2480 N=0
2490 FOR I=1 TO 10
2500 RD1(I)=(1/(4*MUP))*DF*(RD^2-(N*INC)^2)
2510 N=N+1
2520 IF N=10 THEN GOTO 2540
2530 NEXT I
2540 REM
2550 QP1=((PI*RD^4)/(8*MUP))*DF
2560 AVEVP1=(RD^2/(8*MUP))*DF
2570 MAXVP1=(RD^2/(4*MUP))*DF
2580 EL1=.115*(2*RD^2*DEN*1000*AVEVP1)/MUP
2590 REP1=(2*DEN*1000*QP1)/(MUP*PI*RD)
2600 IF REP1>2300 GOTO 2610 ELSE GOTO 2650
2610 CLS
2620 COLOR 30
2630 PRINT "BEWARE OF RESULTS: REYNOLDS NO INDICATES TURBULENT FLOW IN PIPE"
2640 COLOR 7
2650 REM
2660 IF PB=1 THEN GOTO 2930
2670 N=0
2680 FOR I=1 TO 10
2690 ROP(I)=(1/(4*MUPR))*DF*(RD^2-(N*INC)^2)
2700 N=N+1
2710 IF N=10 THEN GOTO 2730
2720 NEXT I
2730 REM
2740 QPP=((PI*RD^4)/(8*MUPR))*DF
```

```
2770 REPP=(2*DEN*(QOC*DPP)/(MUPP*PI*RD)
2780 MAXVPP=(RD^2/(4*MUPP))*DF
2790 IF REPP>2300 GOTO 2800 ELSE GOTO 2840
2800 CLS
2810 COLOR 30
2820 PRINT "BEWARE OF RESULTS: REYNOLDS NO INDICATES TURBULENT FLOW IN PIPE"
2830 COLOR 7
2840 REM
2850 IF PRO$="G" THEN GOTO 2920
2860 IF PRO$="g" THEN GOTO 2920
2870 PRINT
2880 INPUT "ENTER G IF PRINTER SWITCHED ON ";PR$
2890 IF PR$="G" THEN GOTO 2920
2900 IF PR$="G" THEN GOTO 2920
2910 REM
2920 REM *** PRINTOUT ***
2930 REM
2940 LPRINT "FLOW IN A PIPE USING 1 BAR VISCOSITY "
2950 LPRINT "___________________________________ "
2960 LPRINT
2970 LPRINT "CRUSTAL DENSITY (KG M^3) = ";DENC
2980 LPRINT "RADIUS OF PIPE (METERS)  = ";RD
2990 LPRINT
3000 LPRINT "AVERAGE VELOCITY (M SEC^-1) - ";AVEVP1
3010 LPRINT "MAXIMUM VELOCITY (M SEC^-1) - ";MAXVP1
3020 LPRINT "VOLUMETRIC FLOW RATE (M^3 SEC^-1) - ";QP1
3030 LPRINT "REYNOLDS NO                  - ";REP1
3040 IF REP1<2300 THEN GOTO 3070
3050 LPRINT
3060 LPRINT "WARNING - TURBULENT FLOW IN PIPE. DO NOT USE RESULTS "
3070 LPRINT
3080 LPRINT "ENTRANCE LENGTH (METERS)     - ";EL1
3090 LPRINT
3100 LPRINT "VELOCITY PROFILE ACROSS PIPE (CENTER TO MARGIN) IN EQUAL INCREMENTS
 "
3110 LPRINT
3120 LPRINT "CENTER
3130 FOR I=1 TO 10
3140 LPRINT USING "##   ";DP(I);
3150 LPRINT RD1(I)
3160 NEXT I
3170 LPRINT "MARGIN "
3180 IF P9=1 THEN GOTO 3450
3190 LPRINT
3200 LPRINT
3210 LPRINT "FLOW IN A PIPE USING HIGH P VISCOSITY "
3220 LPRINT "___________________________________ "
3230 LPRINT
3240 LPRINT "CRUSTAL DENSITY (KG M^3) = ";DENC
3250 LPRINT "RADIUS OF PIPE (METERS)  = ";RD
3260 LPRINT
3270 LPRINT "AVERAGE VELOCITY (M SEC^-1) - ";AVEVPP
3280 LPRINT "MAXIMUM VELOCITY (M SEC^-1) - ";MAXVPP
3290 LPRINT "VOLUMETRIC FLOW RATE (M^3 SEC^-1) - ";QPP
3300 LPRINT "REYNOLDS NO                  - ";REPP
3310 IF REPP<2300 THEN GOTO 3340
3320 LPRINT
3330 LPRINT "WARNING - TURBULENT FLOW IN PIPE. DO NOT USE RESULTS
3340 LPRINT
3350 LPRINT "ENTRANCE LENGTH (METERS)     - ";ELP
3360 LPRINT
3370 LPRINT "VELOCITY PROFILE ACROSS PIPE (CENTER TO MARGIN) IN EQUAL INCREMENTS
 "
3380 LPRINT
```

```
3410 LPRINT USING "##      ";DP(I);
3420 LPRINT RDP(I)
3430 NEXT I
3440 LPRINT "MARGIN
3450 LPRINT
3460 LPRINT
3470 LPRINT
3480 CLS
3490 LPRINT "FLOW IN A DIKE USING 1 BAR VISCOSITY "
3500 LPRINT "________________________________________ "
3510 LPRINT
3520 LPRINT "CRUSTAL DENSITY (KG M^3) = ";DENC
3530 LPRINT "DIKE WIDTH (METERS)       = ";WD
3540 LPRINT "DIKE LENGTH (METERS)      = ";LD
3550 LPRINT
3560 INC=(.5*WD)/10
3570 N=0
3580 FOR I=1 TO 10
3590 WD1(I)=(1/(2*MUP))*DF*(WD*(N*INC)-(N*INC)^2)
3600 N=N+1
3610 IF N=10 THEN GOTO 3630
3620 NEXT I
3630 REM
3640 AVEVD1=(1/(12*MUP))*(DF)*WD^2
3650 MAXVD1=(1/(2*MUP))*DF*((WD*WD/2)-(WD/2)^2)
3660 QD1=AVEVD1*(WD*LD)
3670 REM
3680 RED1=(DEN*1000*WD*AVEVD1)/MUP
3690 IF RED1>2300 GOTO 3700 ELSE GOTO 3750
3700 CLS
3710 COLOR 30
3720 PRINT "BEWARE OF RESULTS: REYNOLDS NO INDICATES TURBULENT FLOW IN DIKE"
3730 COLOR 7
3740 REM
3750 LPRINT "AVERAGE VELOCITY (M SEC^-1) - ";AVEVD1
3760 LPRINT "MAXIMUM VELOCITY (M SEC^-1) - ";MAXVD1
3770 LPRINT "VOLUMTERIC FLOW RATE (M^3 SEC^-1) - ";QD1
3780 LPRINT "REYNOLDS NO                  - ";RED1
3790 IF RED1<2300 THEN GOTO 3820
3800 LPRINT
3810 LPRINT "WARNING - TURBULENT FLOW IN DIKE. DO NOT USE RESULTS "
3820 LPRINT
3830 LPRINT "VELOCITY PROFILE ACROSS DIKE (MARGIN TO CENTER) IN EQUAL INCREMENTS
 "
3840 LPRINT
3850 LPRINT "MARGIN "
3860 FOR I=1 TO 10
3870 LPRINT USING "##      ";DD(I);
3880 LPRINT WD1(I)
3890 NEXT I
3900 LPRINT "CENTER "
3910 IF P8=1 THEN GOTO 4370
3920 LPRINT
3930 LPRINT
3940 LPRINT
3950 LPRINT "FLOW IN A DIKE USING HIGH P VISCOSITY "
3960 LPRINT "________________________________________ "
3970 LPRINT
3980 LPRINT "CRUSTAL DENSITY (KG M^3) = ";DENC
3990 LPRINT "DIKE WIDTH (METERS)       = ";WD
4000 LPRINT "DIKE LENGTH (METERS)      = ";LD
4010 LPRINT
4020 INC=(.5*WD)/10
4030 N=0
```

```
4050 WDP(I)=(1/(2*MUPR))*DF*(WD*(N*INC)-(N*INC)^2)
4060 N=N+1
4070 IF N=10 THEN GOTO 4090
4080 NEXT I
4090 REM
4100 AVEVDP=(1/(12*MUPR))*(DF)*WD^2
4110 MAXVDP=(1/(2*MUPR))*DF*((WD*WD/2)-(WD/2)^2)
4120 QDP=AVEVDP*(WD*LD)
4130 REM
4140 REDP=(DEN*1000*WD*AVEVDP)/MUPR
4150 IF REDP>2300 GOTO 4160 ELSE GOTO 4200
4160 CLS
4170 COLOR 30
4180 PRINT "BEWARE OF RESULTS: REYNOLDS NO INDICATES TURBULENT FLOW IN DIKE"
4190 COLOR 7
4200 REM
4210 LPRINT "AVERAGE VELOCITY (M SEC^-1) - ";AVEVDP
4220 LPRINT "MAXIMUM VELOCITY (M SEC^-1) - ";MAXVDP
4230 LPRINT "VOLUMETRIC FLOW RATE (M^3 SEC^-1) - ";QDP
4240 LPRINT "REYNOLDS NO                    - ";REDP
4250 IF REDP<2300 THEN GOTO 4280
4260 LPRINT
4270 LPRINT "WARNING - TURBULENT FLOW IN DIKE. DO NOT USE RESULTS "
4280 LPRINT
4290 LPRINT "VELOCITY PROFILE ACROSS DIKE (MARGIN TO CENTER) IN EQUAL INCREMENTS
 "
4300 LPRINT
4310 LPRINT "MARGIN "
4320 FOR I=1 TO 10
4330 LPRINT USING "##     ";DD(I);
4340 LPRINT WDP(I)
4350 NEXT I
4360 LPRINT "CENTER "
4370 LPRINT
4380 LPRINT
4390 LPRINT
4400 LPRINT
4410 LPRINT
4420 PRINT
4430 INPUT "ENTER H TO CHANGE WATER ";W$
4440 IF W$="H" THEN GOTO 4470
4450 IF W$="h" THEN GOTO 4470
4460 GOTO 4540
4470 INPUT "WT % H2O ";O(10)
4480 FACT=O(11)-O(10)
4490 FOR I=1 TO 9
4500 O(I)=O(I)*(FACT/100)
4510 NEXT I
4520 FLAG1=1000
4530 GOTO 1040
4540 INPUT "ENTER P TO CHANGE P AND T ";P$
4550 FLAG1=1000
4560 IF P$="P" THEN GOTO 910
4570 IF P$="p" THEN GOTO 910
4580 PRINT
4590 INPUT "ENTER R TO CHANGE COMPOSITION ";R$
4600 FLAG1=0
4610 IF R$="R" THEN GOTO 830
4620 IF R$="r" THEN GOTO 830
4630 CLS
4640 GOTO 4980
4650 REM
4660 REM *** PRINTOUT ***
4670 REM
```